Supplementary Information:

Rate-sensitive Strain Localization and Impact Response of Carbon Nanotube Foams with Microscale Heterogeneous Bands

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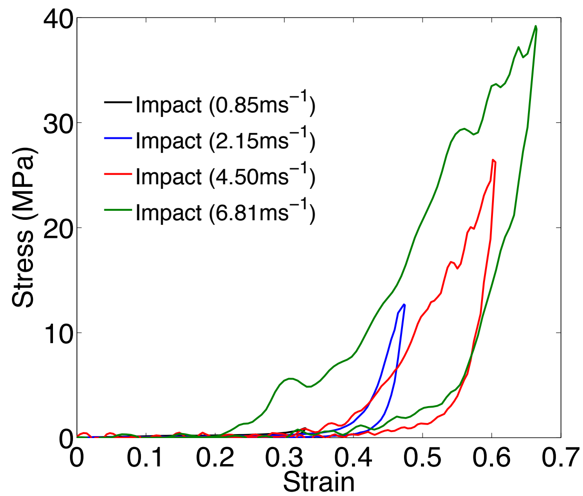
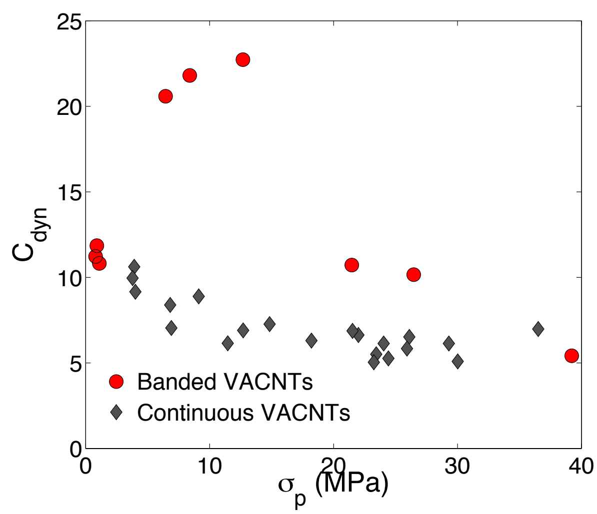
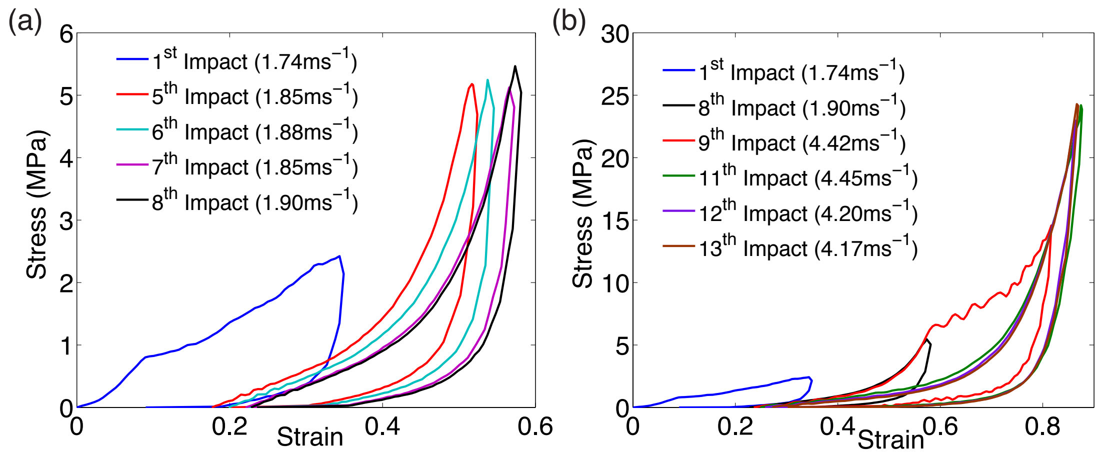


SI Figure 1. Dynamic stress-strain responses of representative samples at four different velocities. For all high velocities impacts, the samples deform at very low stress levels until the two soft bands are compressed and then exhibit rapid stress increase as the stiffest band (Band I) begins to deform.



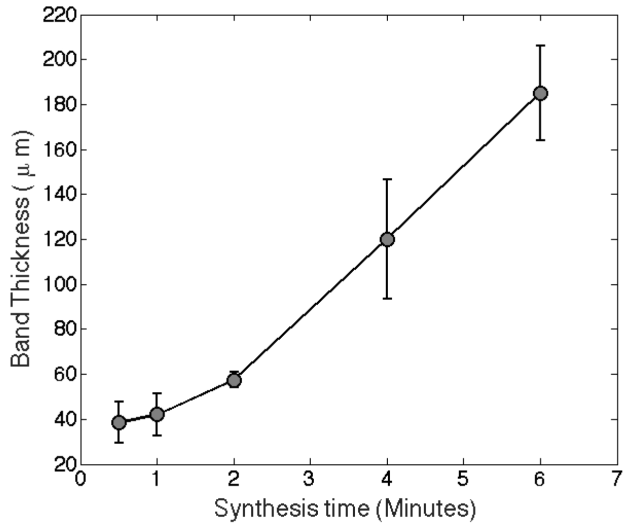
SI Figure 2. The variation of dynamic cushion factor with peak stress reached upon impact for both heterogeneous VACNT foams and continuous VACNT foams.



SI Figure 3. Impact response of a VACNT foam with heterogeneous bands subjected to repeated impacts: **(a)** stress-strain response at low velocity (~1.85 ms^{-1}) impacts, up to 8 impact cycles and **(b)** stress-strain response for higher velocity (~4.3 ms^{-1}) impacts of the same sample in (a), from 9th to 13th impacts (5 cycles).

The impact response of a VACNT foam with heterogeneous bands subjected to repeated impacts is shown in the Supplementary Figure above. A sample was impacted eight times at a low velocity (~1.85 ms^{-1}) (SI Figure (a)). The 1st impact cycle is significantly different from later cycles due to the preconditioning effects discussed in the main study. Due to the resulting decline in hysteresis area, the samples reached increasingly higher strains in repeated cycles, even though the sample was impacted at the same velocity (In strain controlled quasistatic compression experiments, the stress-strain response has been shown to reach a stable response after a few cycles, after which the hysteresis remained the same for consecutive cycles [1–3]).

When the same sample is impacted at a higher velocity (~4.3 ms^{-1}), i.e., beginning with the ninth cycle after the eight impacts discussed above, the loading stress-strain path first followed that of the eighth impact (preconditioned path) up to the maximum strain reached during the 8th impact cycle (SI Figure (b); for comparison, the first and and eighth low velocity impact cycles are included in the figure). After the previous maximum strain is exceeded, the loading path returned back to the initial loading path of a pristine sample (continuous with the first impact cycle) and reached a new maximum strain. This confirms the strain localization in the samples, where only the section of the sample that deforms contributes to impact absorption, with the remaining undeformed section of the sample still capable of absorbing substantial energy in subsequent impacts. A new stable response is reached after several impacts that compress the sample fully (greater than 80% strain) and does not change thereafter (see 11th to 12th impact responses). After reaching this steady-state response, the effect of the soft band is not noticeable anymore and the response becomes similar to that of a continuous VACNT foam. It should be noted that the sample exhibits exceptional resilience to impact by recovering large strains over 80%.



SI Figure 4. The variation of band thickness of the soft middle band with synthesis time.

References

[1] Cao A, Dickrell PL, Sawyer WG, Ghasemi-Nejhad MN, Ajayan PM. Super-compressible foamlike carbon nanotube films. Science 2005;310:1307–10.

[2] Raney J, Fraternali F, Daraio C. Rate-independent dissipation and loading direction effects in compressed carbon nanotube arrays. Nanotechnology 2013;24.

[3] Thevamaran R, Meshot ER, Daraio C. Shock formation and rate effects in impacted carbon nanotube foams. Carbon 2015;84:390–8.